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Transcript of the Paper,

ELECTRON MICROPROBE STUDIES OF MICROMETEORITES

by

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INTRODUCTION

Studies of micrometeorites and cosmic dust are conducted at our laboratory as a part of a broad program investigating the chemical composition of extraterrestrial matter. Samples of fine particles presumed to be of cosmic origin were collected from polar ice caps, deep-sea sediments, soil, the atmosphere, and ancient rocks. Chemical analyses of the particles were done using electron microprobe techniques. Briefly, this method focuses a 0.5-micron-diameter electron beam on the specimen, exciting characteristic X-rays from the elements present. To a first approximation, the intensity of emitted radiation is proportional to the concentration, and it is possible to perform nondestructive quantitative analyses on individual particles as small as 5 microns in diameter.

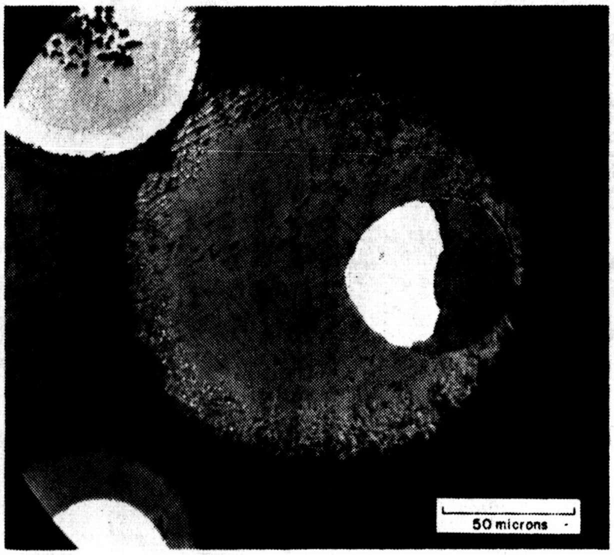
The analytical procedure was as follows: Particles were embedded in plastic and polished according to standard mineragraphic practice. The polished section of each particle was photographed at high magnification to provide a map for guiding analyses. The analyses were conducted in three steps. (1) Qualitative analyses were done to detect the presence of all elements with atomic number 12 to 92 (Mg through U). (2) By sweeping the electron beam over a selected area on the specimen, the distribution of particular elements in the specimen was displayed. (3) Quantitative analyses of elements known to be present were carried out. Characteristic X-ray intensities for the samples were compared to those for chemically analyzed standard minerals, and corrections for wavelength shift, detector dead time, background, atomic number, mass absorption, and secondary fluorescence were applied.

RESULTS

Analyses of natural spherules recovered from Atlantic Ocean sediments will be described, and these data will be compared with artificial spherules produced in an attempt to discover the mechanism of origin.

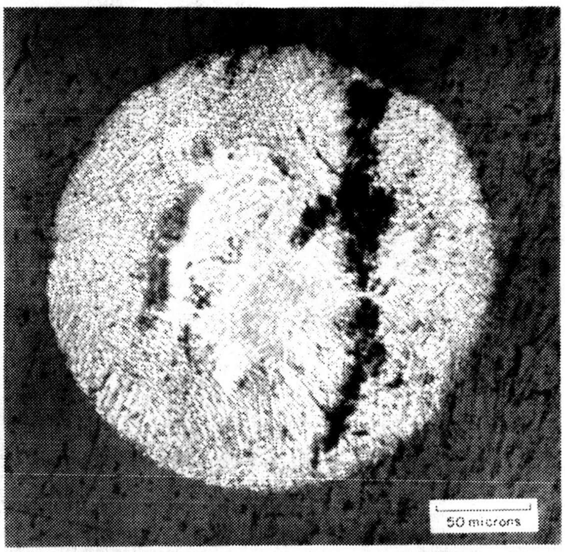
Four groups of particles were recognized in the sediment samples, based on their chemical composition.

POLISHED SECTION OF SPHERULE
FROM ATLANTIC OCEAN SEDIMENTS



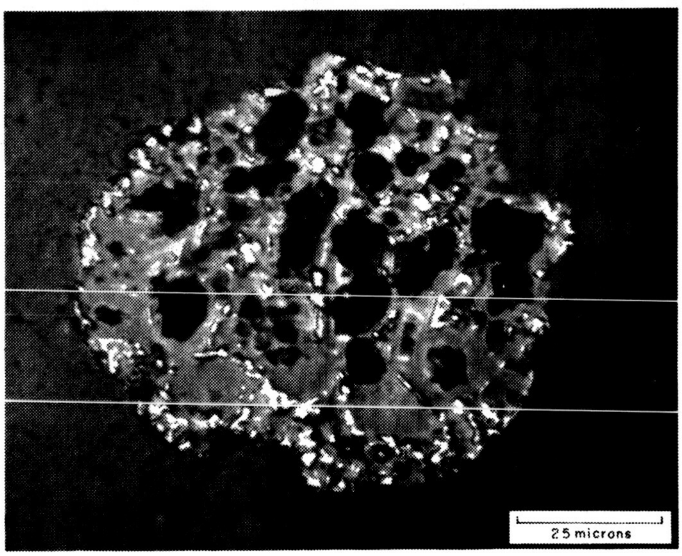
This slide shows an example of a Group 1 spherule. The bright area is metallic Ni-Fe. The other part of the same circle is trevorite ($NiFe_2O_4$), a Ni-bearing magnetite. The main mass of the spherule is magnetite (Fe_3O_4) with up to 1.5% Ni. Darker areas between magnetite grains are rich in Si. The outer portion of the spherule is an oxidized rim. In the upper left of the slide is a Group 2 spherule. This is homogeneous magnetite, with small amounts of Ni and Co. Its composition is similar to the outer rim of Group 1 spherules.

POLISHED SECTION OF SPHERULE
FROM ATLANTIC OCEAN SEDIMENTS



This slide shows a Group 3 spherule. The dendritic texture, lower Fe content, and absence of Ni and Co all distinguish this group of spherules from the others. The lighter lamellae are richer in Si than the darker, more Fe-rich matrix.

POLISHED SECTION OF SPHERULE
FROM ATLANTIC OCEAN SEDIMENTS



This slide shows a Group 4 particle. In contrast to those of other groups, these are irregular and not spherules. It is apparently a mixture

of two different materials. The bright flakes are richer in Ni, and they appear to be embedded in a Ni-poor matrix. The subrounded, dark areas are holes in the specimen, caused by plucking of the porous matrix during sample preparation.

Table 1. Chemical composition of spherules by electron microprobe techniques (wt. percent)

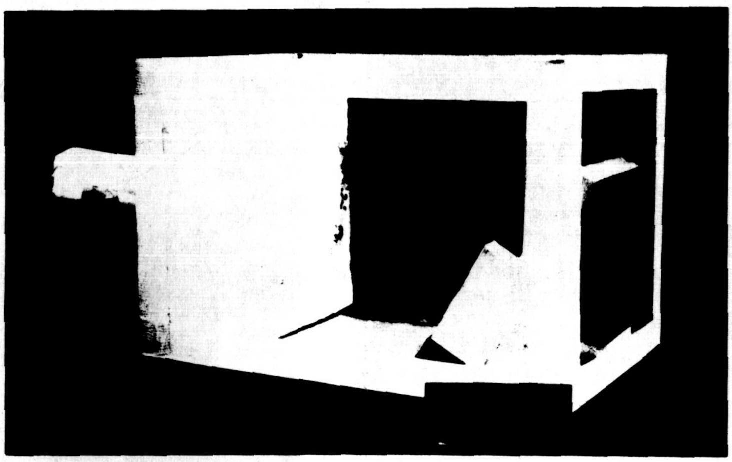
Spherule	Fe	Ni	Co	Mn	Al	Si	P	S	Ca	Ti	Cr	Mg	Other
Group 1													
1 Rim	64.2	1.93	0.27	0.03	0.33	0.20	0.08	<0.02	0.89	<0.02	0.07	0.89	
Trevorite	41.0	20.2	0.38	0.09	0.77	2.70	0.36	0.13	0.87	0.30	<0.03	0.48	tr. V
Ni-Fe	21.6	77.5	1.19	0.08	<0.02	0.05	n.d.	<0.02	0.03	0.04	<0.02	n.d.	
Magnetite	71.0	1.42	0.25	<0.02	0.23	0.14	0.07	<0.02	0.06	<0.02	0.06	<0.02	
Si rich	56.0	n.d.	n.d.	n.d.	n.d.	3.4	n.d.	n.d.	0.60	n.d.	n.d.	n.d.	
5 Rim	64.3	4.02	0.59	0.04	0.09	0.08	<0.02	0.05	<0.02	<0.02	0.13	n.d.	
Magnetite	70.6	3.87	0.56	0.05	0.13	0.05	<0.02	0.04	<0.02	<0.02	0.12	0.13	
6 Rim	67.7	1.08	0.30	n.d.	0.06	0.06	n.d.	n.d.	<0.02	<0.02	n.d.	n.d.	
Trevorite	43.9	18.4	0.53	0.10	n.d.	2.47	0.36	n.d.	0.69	0.05	0.14	0.42	tr. V
Magnetite	71.7	1.13	0.39	0.03	<0.02	<0.02	<0.02	n.d.	<0.02	<0.02	0.18	<0.02	
Group 2													
2	64.6	1.62	0.38	<0.02	<0.02	<0.03	n.d.	<0.02	<0.02	<0.02	<0.02	<0.02	
3	68.2	0.72	0.25	<0.02	<0.02	<0.02	n.d.	<0.02	<0.02	0.09	0.20	<0.02	
12	64.0	0.41	0.20	<0.02	0.06	0.06	<0.02	0.05	<0.02	<0.02	<0.02	<0.02	
Group 3													
7 Lamellae	46.0	n.d.	n.d.	n.d.	n.d.	3.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
Matrix	53.3	0.20	0.15	0.07	1.1	1.7	0.35	0.15	0.40	0.06	0.82	3.60	
8 Lamellae	36.7	<0.02	n.d.	<0.02	0.07	14.0	n.d.	<0.02	1.1	<0.02	<0.02	5.7	
Matrix	63.6	0.05	0.08	<0.02	<0.02	1.70	0.09	<0.02	<0.02	<0.02	0.03	3.0	
Group 4													
4	37.1	0.06	0.04	0.20	1.7	0.78	n.d.	<0.03	0.29	0.26	0.56	0.89	
9 Matrix	42.2	<0.02	0.08	0.32	2.0	1.8	1.33	0.17	1.00	0.90	0.34	1.48	
Flakes	48.0	0.47	n.d.	n.d.	2.0	1.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
10	36.6	<0.02	0.05	<0.02	2.9	2.0	0.69	0.14	0.91	0.70	0.48	1.56	
11	30.3	0.03	0.04	0.23	3.5	0.65	0.91	0.12	0.50	0.42	0.05	1.52	
13	44.4	0.45	0.06	0.16	3.0	0.6	0.04	0.10	0.35	0.28	0.40	1.65	

n.d. = not determined.

This table gives the chemical composition of particles in each group. It is apparent that Group 1 and 2 spherules are rich in Ni and Co, on the order of larger iron meteorites. Their form and texture indicate that they cooled rapidly from a melt. Probably, these spherules represent ablation droplets formed during entry of larger iron meteorites into the earth's atmosphere, and thus are micrometeorites. Modifications of their surfaces apparently took place both in the latter stages of flight through the atmosphere and on the surface of the earth. Particles in Groups 3 and 4 are probably not meteoritic, as they are very poor in Ni and Co and are of different textural patterns. At present, all one can say is that the origin of these particles is uncertain.

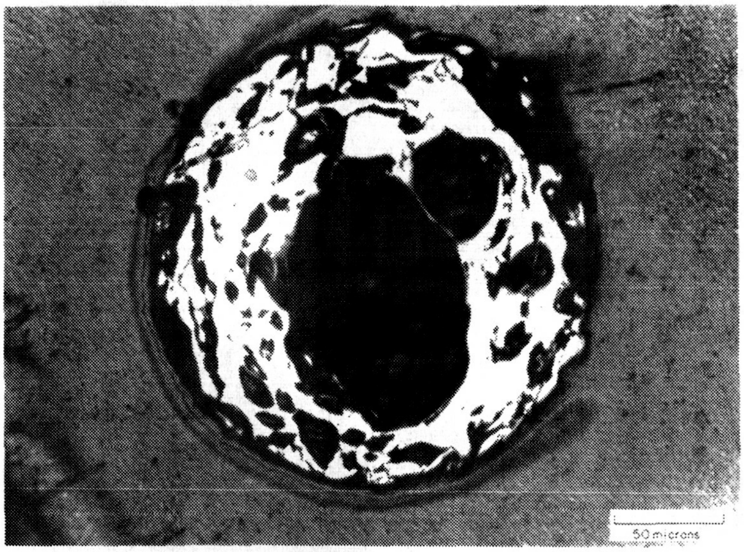
In order to better understand the mechanism of formation of Group 1 and 2 spherules, experiments with steels of approximate meteoritic composition (95% Fe, 5% Ni) were conducted to discover if the basic features of the spherules could be duplicated in the laboratory. Hypervelocity impact was used to produce instantaneous heating, shock, and immediate cooling.

APPARATUS FOR PRODUCTION OF ARTIFICIAL SPHERULES BY HYPERVELOCITY IMPACT AGAINST A Ni-Fe STEEL TARGET



A Ni-Fe steel projectile 3.5 mm in diameter was impacted against a 5 × 5 cm block of the same composition. The velocity of impact was about 5.5 km/sec. The event took place in 0.1 atm of air. In this slide, the projectile entered from the left, struck the target, and ejecta from the impact was sprayed back in a conical pattern and trapped in a white polystyrene foam layer. The darker circle in this foam is the locus of points of ejected particles. Eighty to ninety percent of the ejecta was angular debris showing no composition change. About 10 percent was spherules, indicating that temperatures at least as high as the melting point of Fe (1500° C) had been attained.

SPHERULE PRODUCED BY HYPERVELOCITY IMPACT AGAINST A Ni-Fe STEEL TARGET



This slide shows a polished section of a 100-micron-diameter spherule produced by impact. Note its porous structure. The darker areas are Si-rich segregations, similar to those in natural Group 1 spherules. The main result is that the bulk of this spherule is magnetite (Fe_3O_4) with only 0.5% Ni. Apparently, during impact the Fe "burned," was oxidized to Fe_3O_4, and in this process an order of magnitude of Ni was lost. Preliminary calculations suggest that at least some of the Ni may have been vaporized. A similar experiment was carried out in 0.1 atm of argon, but no spherules were found.

COMPOSITIONS AS OBTAINED BY ELECTRON MICROPROBE TECHNIQUES

SAMPLE	NO. OF ANAL.	CONCENTRATION OF ELEMENTS, wt. percent										
		C	Si	P	S	Cr	Mn	Fe	Ni	C	M	TOTAL
STEEL AiSi E-2512 (COULTER STEEL & FORGE CO.)	—	0.11	0.29	0.008	0.014	0.02	0.52	93.908*	5.01	0.09	0.03	100.00
MICROPROBE ANALYSIS OF AiSi E-2512	70	n.d.	0.27	n.d.	0.01_3	0.05_9	0.64	94.2	5.17	0.02_5	n.d.	100.377
TARGET BLOCK, 2 cm FROM CRATER	72	n.d.	0.24	n.d.	0.01_5	0.05_4	0.70	94.2	5.07	0.02_3	n.d.	100.302
TARGET BLOCK, IMMEDIATE VICINITY OF CRATER	85	n.d.	0.26	n.d.	0.01_3	0.06_0	0.64	94.3	4.97	0.02_5	n.d.	100.268
IMPACT PRODUCED SPHERULE (MAGNETITE)	155	n.d.	0.05	n.d.	0.01	$<0.01_3$	0.55	72.1	0.51	0.01_8	n.d.	—

*CALCULATED VALUE

This table gives the compositional data for the steel experiment. No chemical changes were noted in the target, or in deformed material. However, severe chemical fractionation took place in the spherule to produce a particle with essentially the same composition as the bulk of natural Group 1 spherules.

CONCLUSIONS

1. Electron microprobe analyses of all phases present in suspected cosmic dust particles are needed to properly interpret their origin. At least two groups of probable meteoritic spherules were recovered from Atlantic Ocean sediments.

2. The mechanism of spherule formation appears to have been approximated by hypervelocity impact experiments, in which oxidation of Fe to magnetite and loss of Ni occurs in a fashion similar to that displayed in natural spherules.